NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3142

A FURTHER INVESTIGATION OF THE EFFECT OF SURFACE FINISH ON FATIGUE PROPERTIES AT ELEVATED TEMPERATURES

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SUMMARY

An investigation was conducted to evaluate the effects of surface roughness on fatigue properties of low-carbon N-155 alloy with a grain size of A.S.T.M. 6 and of S-816 alloy with a grain size of A.S.T.M. 6 to 7. Fatigue studies were conducted at 80°, 1200°, 1350°, and 1500° F. In addition, an investigation of the effect of surface abrasion upon the nature, direction, magnitude, and depth of residual stresses and of the effect of time and temperature upon the relief of these stresses was conducted.

The stress concentration effect of the surface roughnesses investigated was found to lower the fatigue strengths of both N-155 and S-816 as much as 10 percent at the temperatures and times considered. This observation was made after the surface compressive stresses induced by roughening, which tend to increase fatigue strength, were reduced by annealing.

A study of strips roughened by abrasion showed that the abraded surface contains compressive stresses at right angles to the scratches and tensile stresses parallel to the scratches. These residual surface stresses may remain during fatigue cycling at low temperatures and when of sufficient magnitude act to appreciably increase fatigue strength. At elevated temperatures, however, these beneficial stresses were relieved during cyclic stressing and only the detrimental stress concentration effects produced by abrasion remained and reduced fatigue strength.

INTRODUCTION

The effect of surface finish on the fatigue properties of the low-carbon N-155 alloy with grain size A.S.T.M. 1 was investigated (ref. 1). In this instance fatigue tests were run at temperatures of 80°, 1000°, 1350°, and 1500° F on specimens of large grained N-155 with three surface finishes: a polished finish having a roughness of 4 to 5 microinches rms, a ground finish having a roughness of 20 to 25 microinches

rms, and a rough finish having a roughness of 70 to 80 microinches rms. The test results indicated that the large-grained N-155 was unaffected by the stress concentration effects of the rough finishes at both room and elevated temperatures; and that the ground finish was relatively stress-free, whereas the polished and rough finishes contained compressive stresses. The magnitude of the compressive stresses in the rough finish was much larger than in the polished finish.

The effects of these same three surface finishes upon the fatigue properties of fine-grained (A.S.T.M. 6) low-carbon N-155 alloy were studied at both room and elevated temperatures in the present investigation at the NACA Lewis laboratory. S-816 alloy (A.S.T.M. 6 to 7 grain size) has also been studied because of the current usage of this material for forged gas-turbine blades. Additional objectives were the investigation of the stresses and cold work induced in surfaces by abrasion with abrasive papers and cloths, and the effect of temperature and time at temperature on the relief of these surface stresses. These additional investigations were conducted to aid in the understanding of the fatigue results from the polished and rough finishes which were prepared using abrasive papers and cloths.

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MATERIALS

Fatigue Investigation

The materials investigated were fine-grained N-155 and S-816. The chemical composition (supplied by the producer), heat treatment, grain size, and hardness after heat treatment are listed in the following tables:

Chemical composition (percent by weight)											
Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N	Fe
N-155	0.13	1.64	0.42	21.22	19.00	19.70	2.90	2.61	0.84	0.13	Bal.
S-816	.37	1.31	.57	20.08	19.21	42.79	4.00	4.03	4.30	----	3.31

Alloy	Heat treatment	A.S.T.M. grain size	Rockwell hardness		Micro-structure
			B	C	
N-155	1 hr at 2200° F; water quenched; 16 hr at 1400° F; air cooled	6	93 to 97		fig. 1
S-816	1 hr at 2150° F; water quenched; 16 hr at 1400° F; air cooled	6 to 7		24 to 26	fig. 2

Heat-treated N-155 bar stock in 5 inch lengths and 1 inch in diameter was obtained from the same heat (heat A-1726) and was part of the material acquired by the NACA for the investigation reported in reference 2. The processing and tensile test properties of the N-155 are reported in reference 2.

The S-816 test specimens were prepared from 1-inch-diameter bar stock obtained from a single heat. The bars were cut into 5-inch lengths before being heat treated at the Lewis laboratory.

Surface Stress Investigation

Strips of N-155 alloy employed in this investigation were 6 inches in length, 3/8 to 1/2 inch in width, and 0.004 to 0.010 inch in thickness. The strips were rolled to the thicknesses desired and then packed between flat plates in an enclosed box and heat-treated in argon as follows: 1 hour at 2200° F, air cooled, 16 hours at 1400° F, furnace cooled. This heat treatment was chosen to produce structures corresponding to that of the N-155 bar stock from which the fatigue specimens were machined.

APPARATUS AND PROCEDURE

Fatigue Evaluation

Method of specimen surface preparation. - The dimensions of all specimens used in this investigation are given in figure 3. The reduced center section of all the specimens was ground in a cylindrical grinder by form grinding with a 60-grit aluminum oxide, vitrified bonded wheel of grade J and density 5. The grinding wheel speed was maintained between 5000 and 7000 surface feet per minute, and the specimen speed for the finishing cut was maintained between 200 and 300 surface feet per minute. This treatment caused circumferential finish marks (ground specimen, fig. 4).

The polished finish was prepared by polishing the ground surface on the specimens with successively finer grades of emery cloth and paper, finishing in the longitudinal direction of the specimen with paper grade 2/0 (polished specimen, fig. 4).

The rough finish was prepared by semipolishing the ground specimens to remove the grinding scratches and then roughening the surface by holding a strip of 46-grit abrasive cloth against a slowly rotating specimen. This treatment also caused circumferential finish marks (rough specimen, fig. 4).

The following table lists the surface roughness, test temperatures, and alloys for each finish. The surface roughness measurements were made in the longitudinal direction with a profilometer.

Surface		Test temperature, °F	
Finish	Roughness (microin. rms)	N-155 specimens	S-816 specimens
Polished	4-5	80, 1350	80, 1200, 1500
Ground	20-25	80, 1350	--------------
Rough	70-80	80, 1350	80, 1200, 1500

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Method of evaluation. - A drawing of the fatigue testing machine is included in a previous report (ref. 1). The specimens were tested as fixed nonrotating cantilevers stressed in completely reversed bending. The specimen assembly was tuned, by means of weights, to a natural frequency of about 120 cycles per second; the excitation was 120 cycles per second, so that the specimen was vibrating near resonance. The stress in the specimen was determined from an approximate equation relating stress to inertia loading at resonance and is believed to be accurate to ±2 percent. Other factors such as specimen dimensions, positioning, and so forth were controlled closely enough to duplicate stress conditions to within ±500 pounds per square inch.

The specimens tested at elevated temperatures were heated to temperature in 1/2 to 1 hour and held at temperature from 2 to 4 hours prior to the start of the test. The temperature was controlled to within ±3° F. The thermocouples were spot welded to the specimens at the failure section along the neutral plane.

Surface Investigation

Preparation of abraded surface strips. - The surfaces of N-155 strips were roughed by hand rubbing abrasive paper or cloth back and forth over the strips either transverse or parallel to the longitudinal dimension. Surface roughness was measured with a profilometer at right angles to the direction of the scratches. The various surface roughnesses and the paper or cloth used in obtaining them are as follows:

Surface roughness, microin. rms	Abrasive paper or cloth
5-10	2/0 emery paper
15-20	2/0 emery cloth
30-35	No. 50 grit cloth
60-70	No. 16 grit cloth

Determination of bending moment in abraded strip. - The magnitude of the bending moment, i.e., surface stress, produced by various finishes was indicated by the deflection of abraded strip. Use was made of the fact that if a residual stress is placed in one side, the strip will arc. The strip will arc away from the surface in compression and toward the surface in tension.

Determination of thickness of stressed layer as related to roughness. - Strips were roughened on one side and successive layers were removed from the roughened side by electrolytic etching until the curved strips became flat. The total depth of material removed from the stressed side necessary to allow the strip to become flat was the approximate depth of the stressed layer.

Determination of amount of cold work in stressed layer. - The width of X-ray diffraction lines for most metals increases with the amount of cold work (measured by hardness) in the metal. Use was made of this characteristic to determine the amount of cold work in abraded surfaces by comparing the width of the (111) $K\alpha$ doublet diffraction line from abraded surfaces with the width of this line from cold-rolled strips of various hardnesses, that is, corresponding to different amounts of cold work. The width of this diffraction line was measured at 1/2 maximum intensity; the diffraction line was obtained with a chart-recording Geiger counter X-ray spectrometer using a chromium target tube. The primary X-ray beam entered the surface and the diffracted beam left the surface of the strips at an angle of $33\frac{1}{2}^{\circ}$. A calibration curve of cold work against line width was first obtained for strips of N-155 reduced in thickness various amounts by cold rolling. Rockwell superficial hardness measurements using a 15 kilogram load were made on the cold-rolled strips to obtain the surface hardness. These superficial hardnesses were converted to Brinell hardnesses by use of conversion tables.

Determination of magnitude of surface stress induced by abrasion. - If a strip which is abraded on one side is curved so that additional compressive stresses are introduced to cause compressive yielding, the magnitude of the residual compressive stress may be approximated as the difference between the yield strength and the added stress. The stress necessary to superimpose upon the residual surface stresses produced by different amounts of roughness was determined by curving abraded strips around curved surfaces of successively smaller radii with the abraded

side of the strips inward until yielding, as detected by a decrease in the original deflection, occurred in the abraded surface. The compressive yield point of the surface layer material was determined by stressing annealed strips in the manner indicated. To insure that compressive and not tensile yielding occurred, the back sides of these strips were abraded to introduce compressive stresses.

Determination of effect of temperature and time at temperature upon relaxation of residual stresses. - The effect of temperature and time at temperature on the relaxation of surface stresses induced by abrading was determined by annealing strips abraded on one side between flat plates and measuring the center deflection remaining in the strip after annealing. The strips were held between flat plates to duplicate the surface stress conditions in the fatigue specimens where these surface stresses cannot be reduced by bending. Strips abraded in the transverse direction and having different thicknesses and roughnesses were annealed for 4 hours each at a series of increasing temperatures. After annealing, these strips were furnace cooled to room temperature. They were then removed from between plates and the center deflection was measured. An abraded strip was also heated at 1200° F, and after various amounts of time at temperature, the center deflection was measured after furnace cooling to room temperature.

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RESULTS AND DISCUSSION

Fatigue Tests

Tests on N-155. - The test results on the specimens of fine-grained N-155 with ground, polished, and rough finishes at 80° F are tabulated in table I and plotted in figure 5(a). The strength of the polished finish was higher than that of the ground, and the strength of the rough finish was slightly higher than that of the polished.

Specimens with these three finishes were then annealed at 1400° F for 4 hours to reduce the magnitude of any residual stresses present in the surfaces and tested to determine the effect of surface roughnesses alone on the fatigue strength. The test results on the specimens with the annealed finishes are tabulated in table II and plotted in figure 5(b), which contains for comparison the curves from figure 5(a) for the unannealed finishes. The strength of the annealed ground finish was approximately the same as that of the unannealed ground finish, which would indicate that if there were any residual stresses present in the ground finish, the stresses were relieved by surface yielding during fatigue cycling or were so small that they were not affected appreciably by the annealing treatment.

The fatigue strength of specimens with annealed polished finishes appears to be slightly higher than that of specimens with unannealed polished finishes. However, the scatter of the results on the annealed polished specimens is so great that it is impossible, considering the limited number of specimens tested, to determine definitely whether the

strengths of the specimens with annealed polished finishes are higher than those of the specimens with unannealed polished finishes.

The strength of the annealed rough finish was below that of the unannealed rough finish, showing that the unannealed rough finish had contained compressive stresses that remained during fatigue cycling to increase the fatigue strength.

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Some of the annealed polished specimens were repolished prior to testing. The repolished annealed specimens had the same strength as the unannealed polished specimens, showing that the annealing treatment had not changed the fatigue strength of the material, and thus making it possible to compare the effects of the annealed and unannealed finishes directly.

In comparing the strengths of the annealed finishes, those of the annealed rough and annealed ground finishes were about 10 percent less at 5×10^7 cycles than that of the annealed polished finish. For the large-grained N-155 no difference was found between the strengths of the polished annealed and rough annealed specimens (ref. 1). The data reported herein show that at room temperature the fine-grained N-155 was sensitive in fatigue to stress concentration effects of surface roughness, whereas the coarse-grained material was not.

The results on the N-155 specimens at 1350° F are tabulated in table I and plotted on figure 5(c). The strength of the rough finish is about 8 percent less at 5×10^7 cycles than that of the polished, showing that surface stress relief occurred by annealing or dynamic yielding or both. These results also show that the fine-grained N-155 is sensitive to the stress concentration effects of surface roughness at 1350° F. For the coarse-grained N-155 (ref. 1), the strength of specimens of all three finishes was the same at this temperature. A similar relation for grain size and fatigue notch sensitivity was found for steels (ref. 3).

Comparison of only the effects of stress concentration produced by surface roughness at 80° and 1350° F on the fine-grained material indicates that the roughness does reduce fatigue strength at both temperatures and that, on a percentage basis, the damage due to the rough finish is of similar magnitude at both temperatures (10 percent decrease in strength at 80° F and about 8 percent decrease at 1350° F). The reason that the rough finish produced greater stress concentration effects than the ground finish at 1350° F but not at 80° F (i.e., after annealing) is not known. This could be a statistical effect, or perhaps there is a more complete relief of stress at 1350° F than after annealing and then running at 80° F.

<u>Comparison of fatigue strengths of fine- and coarse-grained N-155</u>. - At 80° F the fatigue strengths for the fine-grained material having polished and ground finishes were generally better than for the coarse-grained material of reference 1. (This was not true for fewer than about 10^6 cycles.) The strengths of the rough finishes were about the same for the two materials.

At 1350° F the fine-grained material was better than the coarse-grained material at any of the three finishes. Since the N-155 alloy used in the present investigation and that of reference 1 were of different heats, these effects may be due to this variable rather than to grain size alone. Higher fatigue strengths for polished specimens fabricated from fine-grained material were found for other alloys, however (refs. 4 to 10).

Tests on S-816. - The fatigue results on the S-816 specimens at 80° F are tabulated in table III and plotted in figure 6(a). All specimens were annealed at 1400° F for 4 hours. All specimens were tested with annealed surface finishes except one specimen which was polished and one specimen which was roughened after the annealing treatment. The strength of the specimen with the annealed and reroughened finish is much higher than the fatigue curve for the specimens with the annealed rough finishes, showing that the rough finish contains compressive stresses. The strength of the specimen with the annealed and repolished finish appears to be slightly greater than that of the annealed polished specimens, indicating the possibility of compressive stresses in the polished finish. A comparison of the lower strength of the specimens with the annealed rough finish with the strength of the specimens with the annealed polished finish shows that the compressive stresses have been reduced to such an extent that sensitivity of S-816 in fatigue at 80° F to stress concentration effects produced by roughened surfaces is apparent.

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The test results on the S-816 specimens at 1200° and 1500° F are tabulated in table III and plotted in figures 6(b) and 6(c). The fatigue strength of the polished specimens is higher than that of the rough specimens at both temperatures, showing that relief of surface stress occurred and that fine-grained S-816 is sensitive to stress concentration effects induced by surface roughness at these temperatures.

Examination only of the effects of stress concentration produced by surface roughness on S-816 at room and elevated temperatures shows that surface roughness reduces the strength at all temperatures. With strength at 5×10^{7} cycles as a criterion, the rough finish reduced the strength about 10 percent at 80° F, 4 percent at 1200° F, and 8 percent at 1500° F.

Comparison of S-816 and N-155. - Fine-grained S-816 has superior fatigue strength to fine-grained low-carbon N-155 at 80° F. At 1500° F, S-816 has fatigue strengths comparable with those of N-155 at 1350° F. Neither alloy appears to have a particularly greater sensitivity to stress concentration during fatigue under the present conditions.

Surface Investigation

Amount of surface roughness and magnitude and direction of bending moment. - One strip (0.010 in. thick) was roughened in the transverse direction with successively coarser grades of abrasive paper and cloth, and the deflection produced by each degree of roughness was measured. The surface roughness is plotted against the deflection at the center of the strip in figure 7. The results on this strip show that compressive stresses are set up at right angles to the direction of the scratches, since the strip arced longitudinally away from the abraded side, and that the bending moment (which is a measure of stress depth and stress magnitude) increased rapidly with the roughness of the surface.

Another strip (0.010 in. thick) having the same dimensions as the first was abraded in the longitudinal direction in steps with successively coarser grades of abrasive paper and cloth, and the deflection produced by each roughness was measured. The results of this strip are included on figure 7. No measurable deflection was produced in this strip by a roughness of 5 to 10 microinches rms. Longitudinal polishing of a thinner strip (0.005 in. thick) produced measurable deflection at this roughness. At a roughness of 10 to 15 microinches, a small negative longitudinal deflection (i.e., bending toward the abraded surface) was produced in the 0.010-inch-thick strip, showing that some tensile stresses were set up in the same direction as the scratches. At the higher roughnesses of 30 to 35 and 60 to 70, the first few longitudinal scratches on either a partially abraded or a completely abraded strip caused the strip to deflect in the negative direction, and as the abrading was continued, the deflection became constant. As the abrading was continued, the strip arced across its width because the compressive stresses set up at right angles to the direction of the scratches stiffened it in the longitudinal direction. This increased stiffness probably prevented further negative deflection with continued abrasion, even though tensile stresses may have continued to be set up in the same direction as that of the scratches.

Effect of roughness on thickness of surface stressed layer. - The thickness of the stressed layer against the surface roughness is plotted on figure 8. The depth of the stressed layer produced by abrasion is very thin as compared with the depth of the stressed layer produced by shot peening or cold-rolling. As would be expected, the thickness of the stressed layer increases with the roughness of the surface. With the coarse-grained N-155 of reference 1, the fatigue tests showed that the polished material (with a surface roughness of 4 to 5 microin. rms) contained compressive stresses that appreciably increased fatigue strength. Comparison of these fatigue data with the data herein on abraded strips indicate that a compressively stressed layer as shallow as 0.0003 inch may appreciably increase fatigue strength.

Amount of cold work in abraded surfaces. - The width of the (111) diffraction line of the cold-rolled strips is plotted against the percent

of reduction and the surface hardness in figure 9. Values of surface roughness corresponding to line width are placed on this curve. The results show that the abraded surfaces contain a large amount of cold work. The amount of cold work in the abraded surfaces with roughness of 30 to 35 and 60 to 70 is equivalent to the cold work in a strip re duced 50 to 70 percent in thickness (Brinell hardness of 380) by rolling. The diffraction line width increased with surface roughness up to roughnesses of 30 to 35 microinches rms. The reduction in line widths obtained for surface roughnesses less than 30 microinches rms may be due in part to penetration of the X-rays through the thinner abraded layer on these surfaces into the interior material, as well as to a lesser amount of lattice distortion. 2804

Magnitude of surface stress induced by abrasion. - The stress necessary to add to the residual stress in abraded surfaces of various roughnesses for surface yielding is plotted in figure 10. The yield point of the surface layer determined for annealed material was 40,000 pounds per square inch. The yield point of the material in the abraded surfaces is probably much higher as a result of the cold work in the abraded surfaces. A proportional limit of 112,000 pounds per square inch is reported for N-155 having a Brinell hardness of 323 produced by rolling (ref. 10). If the yield point of 40,000 pounds per square inch is considered as the yield point of the abraded surface material, the results show a residual compressive stress of approximately 15,000 pounds per square inch for a roughness of 5 to 10 microinches rms and a compressive stress of approximately 30,000 pounds per square inch for a roughness of 60 to 70 microinches rms. If the effect of the cold work placed in the surface by abrading on the yield point is considered, the magnitude of the residual compressive stress would be of the order of 100,000 pounds per square inch for the surfaces with roughnesses of 30 to 35 and 60 to 70 microinches rms.

Effect of temperature and time at temperature on relaxation of residual surface stresses. - The annealing temperatures are plotted against the deflection remaining in the strip after annealing for 4 hours at each temperature shown in figure 11. Some reduction in center deflection occurred after 4 hours at the annealing temperature of 1000° F, revealing that a temperature of 1000° F does reduce the magnitude of the surface abrasion stresses and also that the magnitude of the abrasion stresses was sufficiently high for some measurable stress relaxation to occur at a temperature of 1000° F. Twenty-six percent of the original center deflection remained in the strip of roughness 60 to 70 microinches rms after annealing at 1400° F for 4 hours. This would indicate that the annealing treatment of 4 hours at 1400° F used for stress-relieving the finishes on the fatigue specimens may not completely remove the compressive stress in the rough finish.

One strip with surface roughness 60 to 70 microinches rms, abraded in the transverse direction, was held at 1200° F for 250 hours to determine the effect of time at temperature on the relaxation of residual surface stresses. The test was interrupted occasionally, the strip cooled to room temperature, and the center deflection of the strip measured. The results are plotted on figure 12 and show that most of the relaxation of the stresses occurs within the first few hours at temperature. After 250 hours at 1200° F, the center deflection remaining in the strip was 26 percent of the original center deflection.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effect of surface finish on fatigue at elevated temperatures for two high-temperature alloys:

1. The stress concentration effect of the surface roughnesses investigated lowered the fatigue strengths of both S-816 and N-155 as much as 10 percent at the temperatures and times considered. This observation was made after the surface compressive stresses induced by roughening which tend to increase fatigue strength were reduced by annealing.

2. The strip tests results show that a surface abraded with abrasive papers and cloths contains compressive stresses at right angles to the scratches and tensile stresses parallel to the scratches. These surface residual compressive stresses in fine-grained low-carbon N-155 are very high, and the amount of cold work may be equivalent, on the basis of X-ray diffraction measurements, to that introduced into a cold-rolled strip reduced 70 percent in thickness.

3. Residual surface compressive stresses may remain in the surface during fatigue cycling at lower temperatures and may act to increase the fatigue strength appreciably.

4. Annealing for 4 hours at 1400° F of specimens of N-155 and S-816 with circumferentially abraded surfaces reduces the fatigue strength at room temperature. The study of similar surfaces on abraded strips shows that for N-155 the magnitude of the surface stress set up by abrasion decreases when the temperature of annealing is as low as 1000° F, and that after a few hours at 1400° F the magnitude of the residual stress remaining is a small fraction of the original stress.

5. At elevated temperatures, these stresses and their effects are reduced by annealing and perhaps by dynamic yielding during cyclic stressing and thus do not cause marked increase in fatigue strength.

6. It is indicated that compressively stressed layers of the order of 0.0003 inch may appreciably increase fatigue strength.

7. Fine-grained N-155 was much more sensitive to the stress concentration effects of surface roughness than coarse-grained N-155 previously reported.

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TABLE I. - RESULTS OF FATIGUE TESTS ON SPECIMENS

OF LOW-CARBON N-155

Temperature, 80° F			Temperature, 1350° F		
Specimen	Maximum stress (lb/sq in.)	Cycles to failure	Specimen	Maximum stress (lb/sq in.)	Cycles to failure
Ground finish					
JE19	58,300	302,000	JS19	43,500	129,000
JX22	49,900	1,944,000	JV22	42,000	1,080,000
JY20	47,200	40,000,000	JH21	39,900	40,250,000
----	------	----------	JN15	39,400	101,217,000[a]
Polished finish					
JB20	65,000	388,000	JT20	46,400	172,000
JS20	58,800	2,764,000	JW20	44,100	1,771,000
JC19	57,100	1,598,000	JL17	42,200	4,363,000
JK21	55,700	1,640,000	JE20	40,700	43,300,000
JI20	54,000	1,252,000	JC24	39,500	13,000,000
JJ17	52,800	18,400,000	JY24	39,200	118,000,000[a]
JW19	52,500	6,000,000	----	------	-----------
Rough finish					
JP18	62,200	1,080,000	JF19	43,000	216,000
JI19	58,100	1,555,000	JN14	42,200	778,000
JJ16	56,900	1,600,000	JE25	39,800	6,130,000
JN16	55,700	29,400,000	JB18	38,400	7,040,000
JW24	52,500	30,000,000	JO20	36,300	54,700,000

[a]Unbroken.

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TABLE II. - RESULTS OF FATIGUE TESTS ON SPECIMENS OF N-155

HELD FOR 4 HOURS AT 1400° F PRIOR TO TESTING AT 80° F

Specimen	Maximum stress (lb/sq in.)	Cycles to failure	Specimen	Maximum stress (lb/sq in.)	Cycles to failure
Ground finish			Polished finish		
JB19[b]	52,800	1,470,000	JU22[b]	62,700	1,250,000
JV24[c]	48,300	6,900,000	JK19[b]	60,600	1,210,000
JU25[c]	47,000	47,200,000	JH23[c]	58,800	864,000
----	------	-----------	JT23[c]	55,500	6,450,000
----	------	-----------	JO17[b]	52,900	13,040,000
----	------	-----------	JW23[c]	52,900	102,000,000[a]
Rough finish			Repolished after annealing		
JO18[b]	54,000	822,000	JS23[c]	60,100	1,470,000
JY19[b]	52,400	1,640,000	JL22[c]	55,400	3,410,000
JB25[c]	50,300	2,200,000	JX24[c]	53,900	5,188,000
JK22[c]	47,300	19,000,000	JO21[c]	51,900	24,700,000
JK23[c]	44,500	107,000,000[a]	----	------	----------

[a]Unbroken.
[b]Heated in air.
[c]Heated in purified argon.

TABLE III. - RESULTS OF FATIGUE TESTS ON SPECIMENS OF S-816

[a]Temperature, 80° F			Temperature, 1200° F			Temperature, 1500° F		
Specimen	Maximum stress (lb/sq in.)	Cycles to failure	Specimen	Maximum stress (lb/sq in.)	Cycles to failure	Specimen	Maximum stress (lb/sq in.)	Cycles to failure
Polished finish								
AC24	84,800	450,000	AB26	71,700	172,000	AC9	49,000	172,000
AC12	80,000	690,000	AB10	71,000	1,212,000	AC2	45,000	2,810,000
AC19	76,300	1,600,000	AB3	68,000	4,190,000	AB22	44,400	2,200,000
AC13	76,200	1,550,000	AB1	66,000	9,150,000	AB19	42,800	3,890,000
AC20	74,600	15,100,000	AB4	64,000	103,000,000[b]	AB12	40,000	32,500,000
AC22	72,600	92,200,000[b]	----	------	----------	AC4	37,800	55,600,000
AC14[c]	79,000	2,203,000	----	------	----------	----	------	----------
Rough finish								
AC17	75,600	475,000	AB23	69,000	173,000	AC8	42,800	432,000
AC23	71,200	1,040,000	AB9	68,300	302,000	AC6	40,400	1,680,000
AC15	68,800	2,200,000	AB8	64,500	9,970,000	AB18	36,700	28,400,000
AC16	65,000	2,760,000	AB25	63,500	87,300,000[b]	AC10	34,900	113,000,000
AC18	64,900	92,200,000[b]	----	------	----------	----	------	----------
AC21[d]	78,400	26,400,000	----	------	----------	----	------	----------

[a]Specimens held for 4 hr at 1400° F in 3 micron vacuum prior to testing unless otherwise noted.
[b]Unbroken.
[c]Polished after annealing.
[d]Roughened after annealing.

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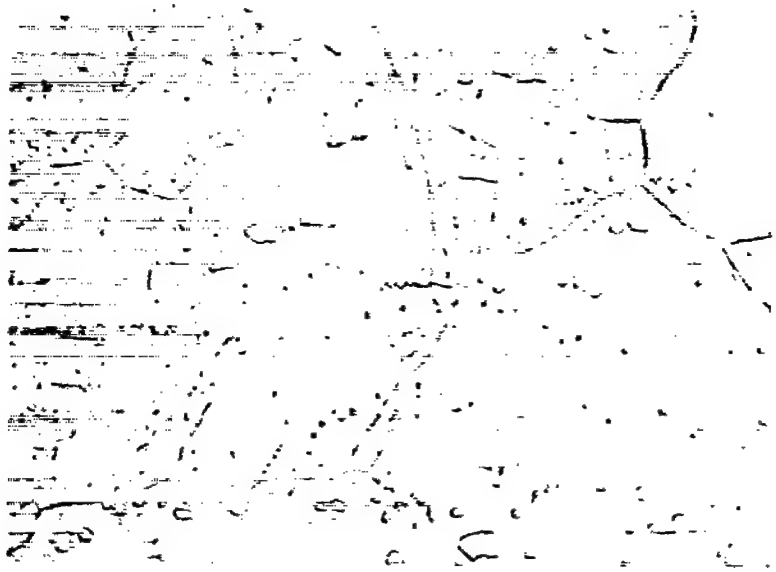
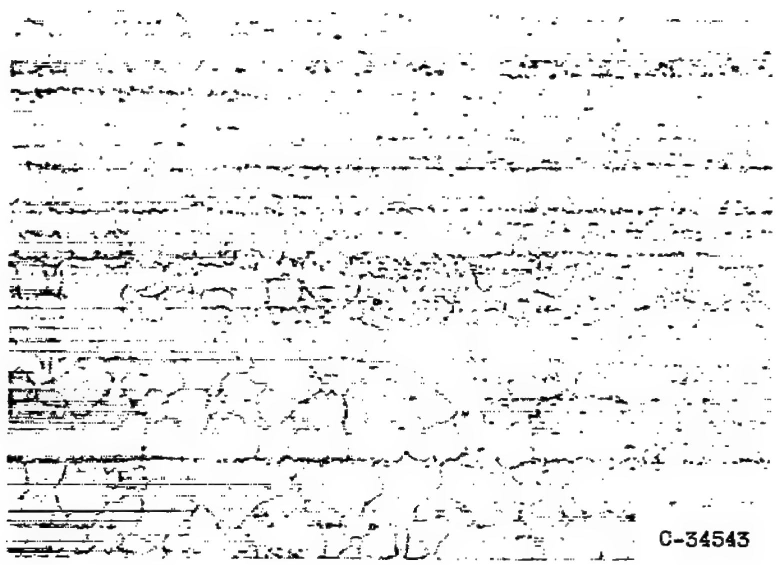
CF-3



(a) X1000.



(b) X100.

Figure 1. - Microstructure of low-carbon N-155 bar stock. Heat-treatment; 1 hour at 2200° F; water quenched; 16 hours at 1400° F; air cooled. Etched electrolytically with 10 percent chromic acid solution.

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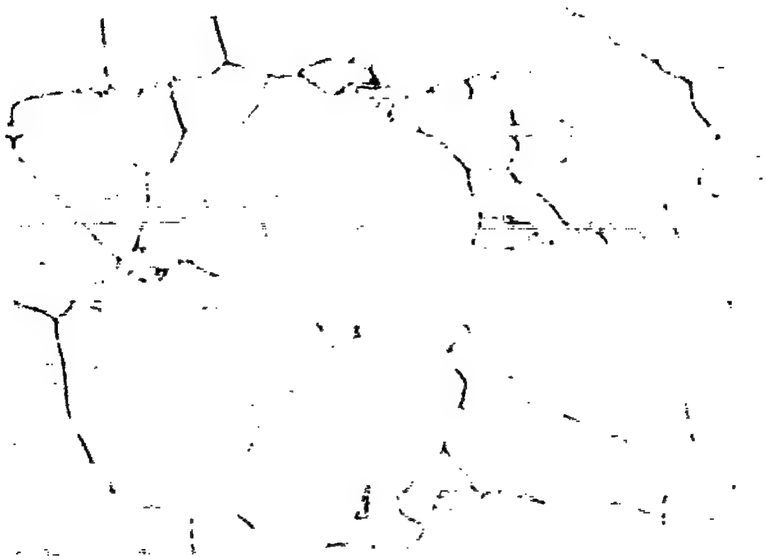
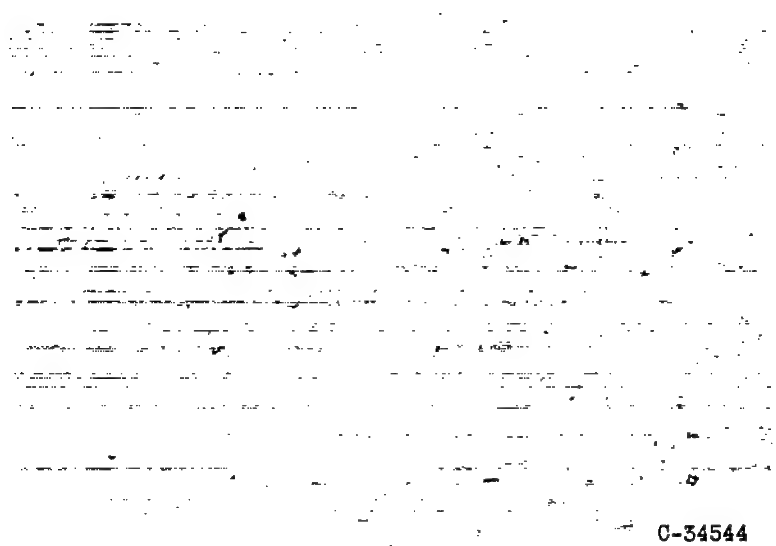


(a) X1000.



(b) X100.

Figure 2. - Microstructure of S-816 bar stock. Heat-treatment; 1 hour at 2150° F; water quenched; 16 hours at 1400° F; air cooled. Etched electrolytically with 50 percent aqua regia, 50 percent glycerine solution.

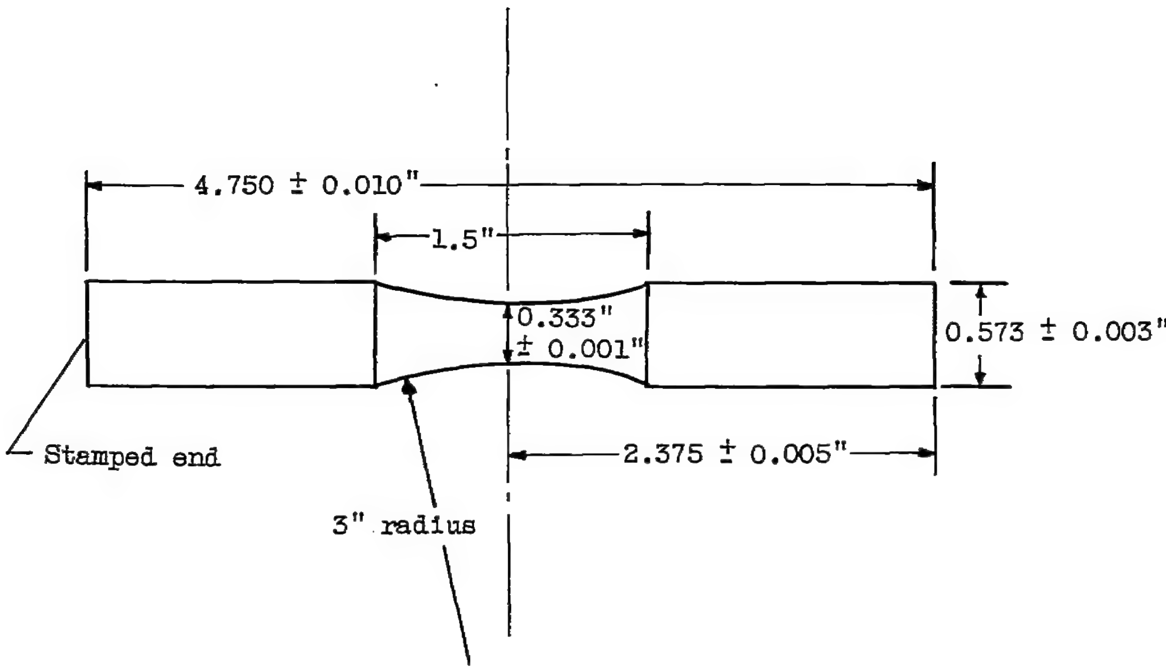


Figure 3. - Dimensions of fatigue specimen.

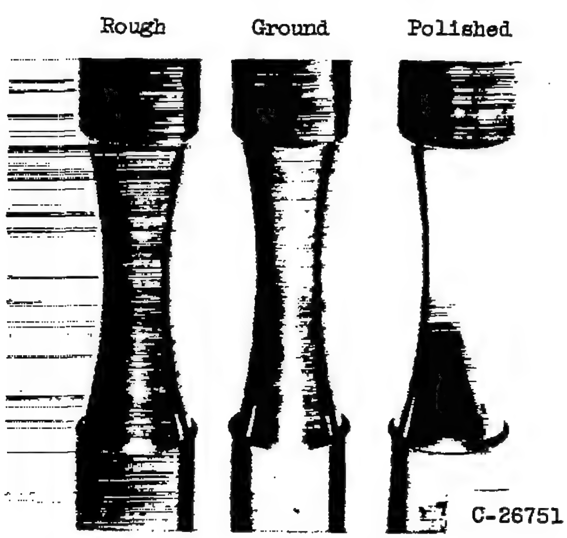
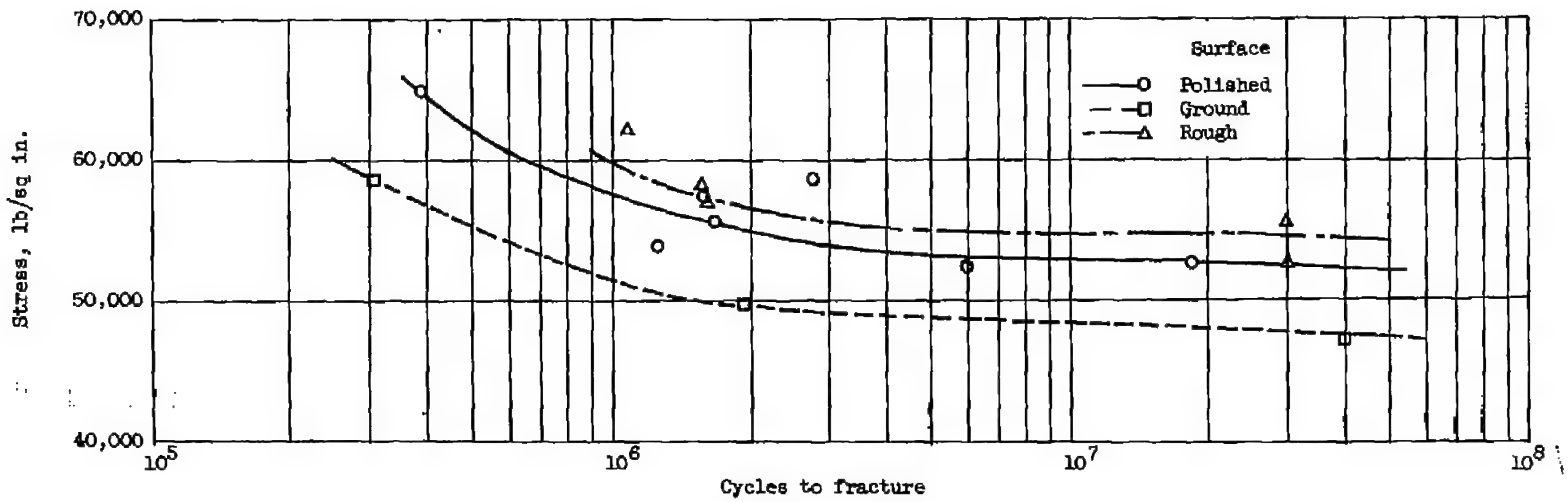
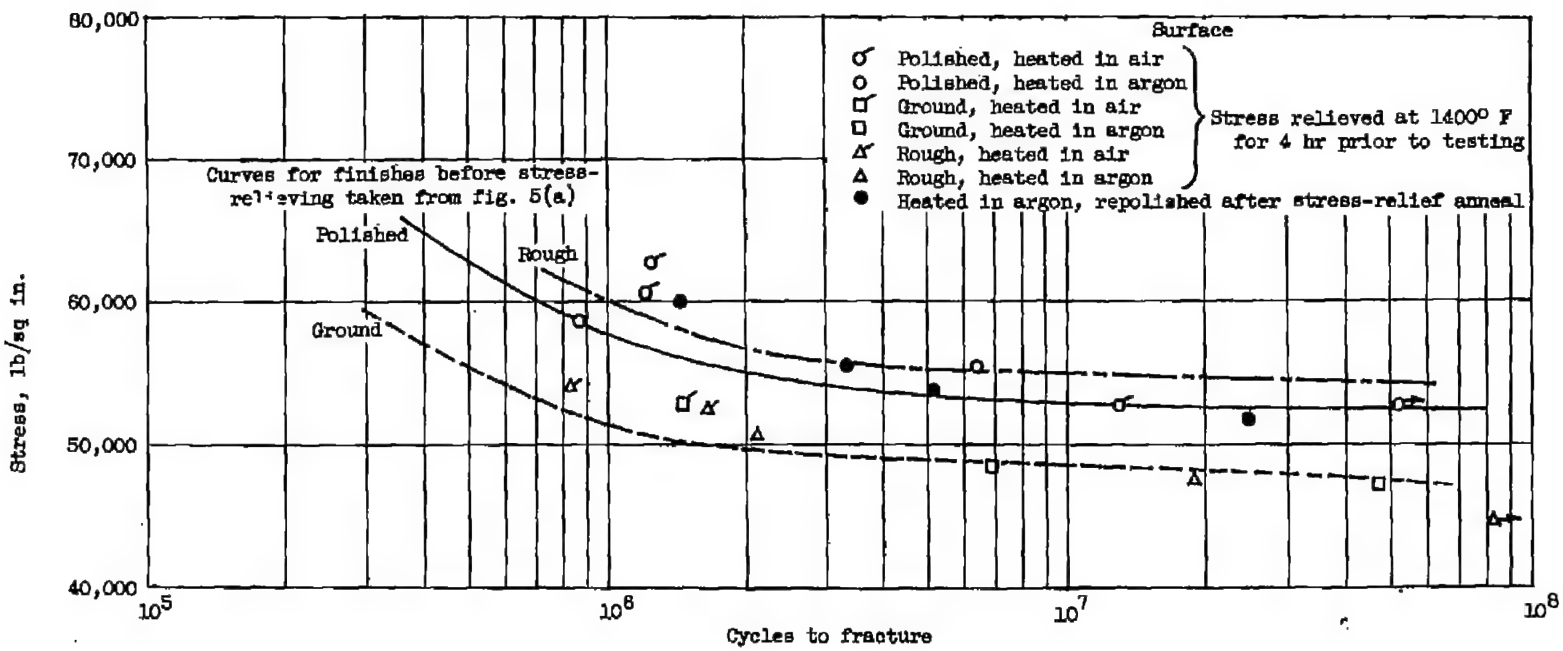


Figure 4. - Fatigue specimens.



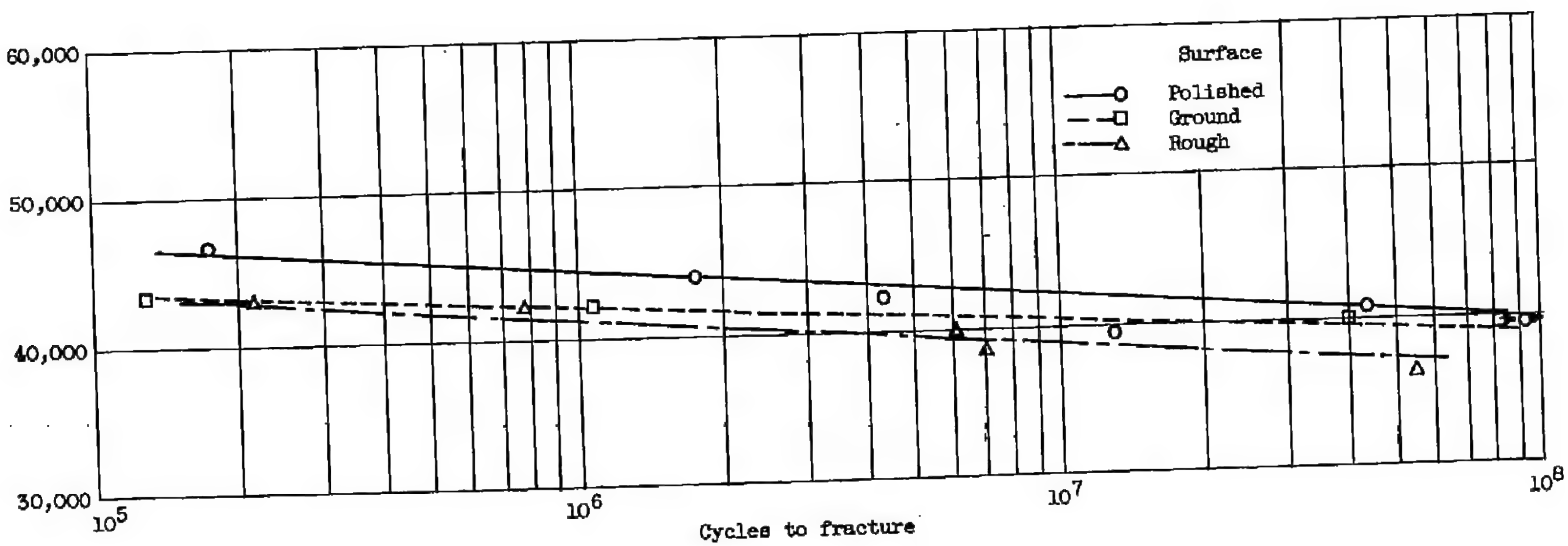
(a) Temperature, 80° F.

Figure 5. - Effect of surface finish on fatigue properties of fine-grained low-carbon N-155.



(b) Temperature, 80° F; fatigue strength of specimens held at 1400° F for 4 hours.

Figure 5. - Continued. Effect of surface finish on fatigue properties of fine-grained low-carbon N-155.



(c) Temperature, 1350° F.

Figure 5. - Concluded. Effect of surface finish on fatigue properties of fine-grained low-carbon N-155.

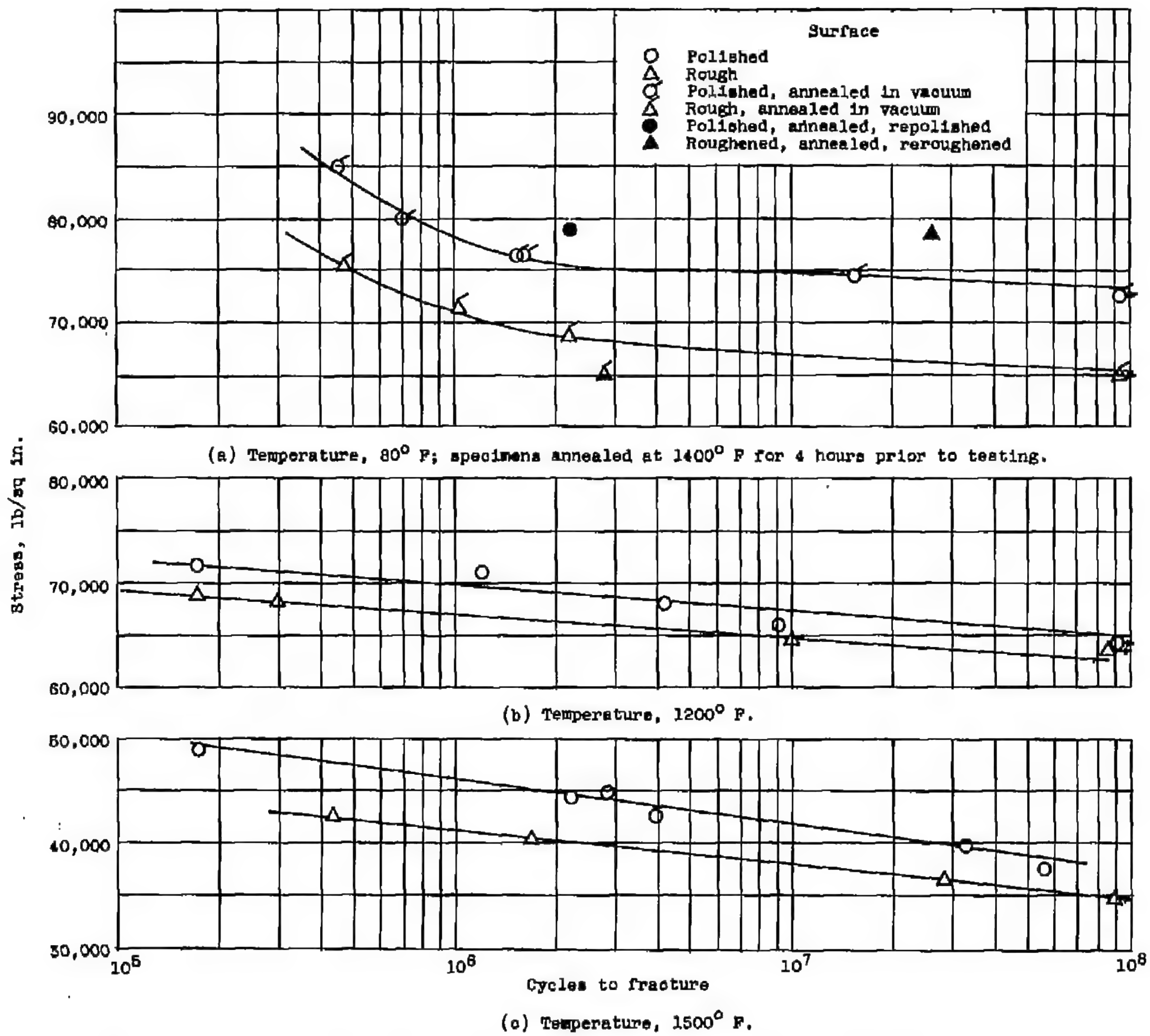


Figure 8. - Effect of surface finish on fatigue properties of S-816.

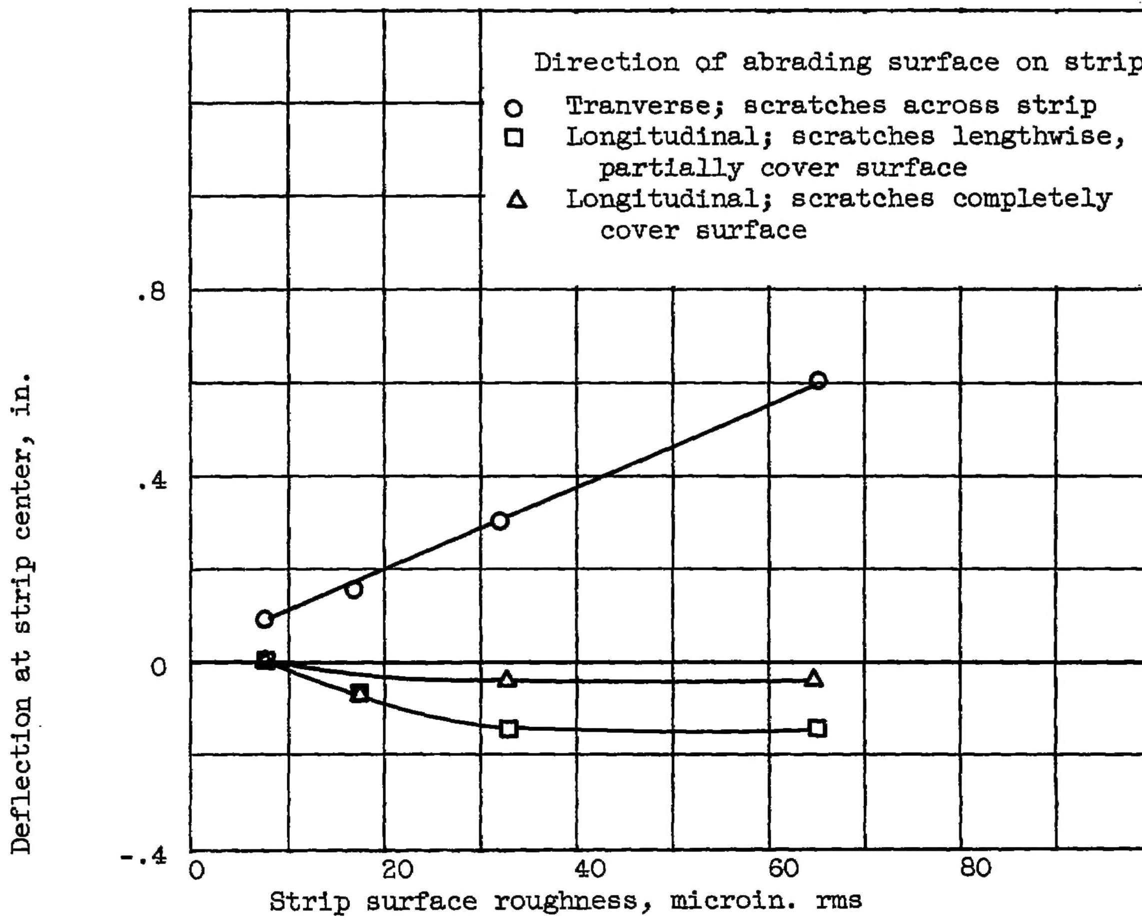


Figure 7. - Effect of surface roughness and direction of abrading on deflection induced in strips of N-155 by abrading one surface.

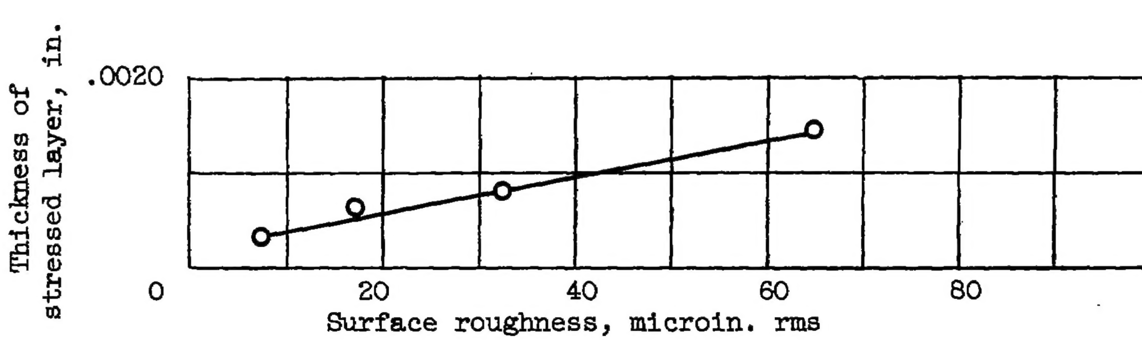


Figure 8. - Effect of roughness on thickness of stressed surface layer induced in N-155 strips by abrading.

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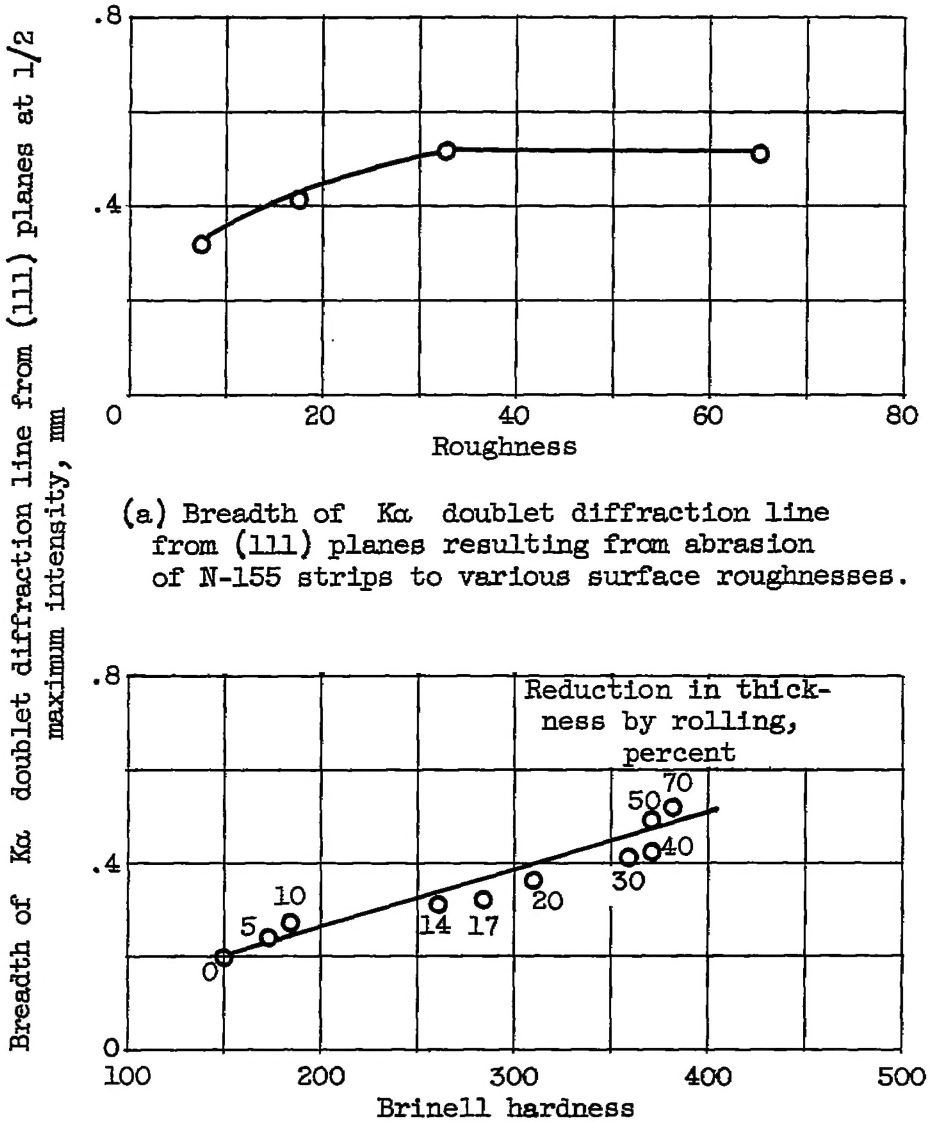

(a) Breadth of Kα doublet diffraction line from (111) planes resulting from abrasion of N-155 strips to various surface roughnesses.

(b) Breadth of Kα doublet resulting from cold-rolling N-155 to various hardnesses.

Figure 9. - Amount of cold work induced in N-155 strips by abrading.

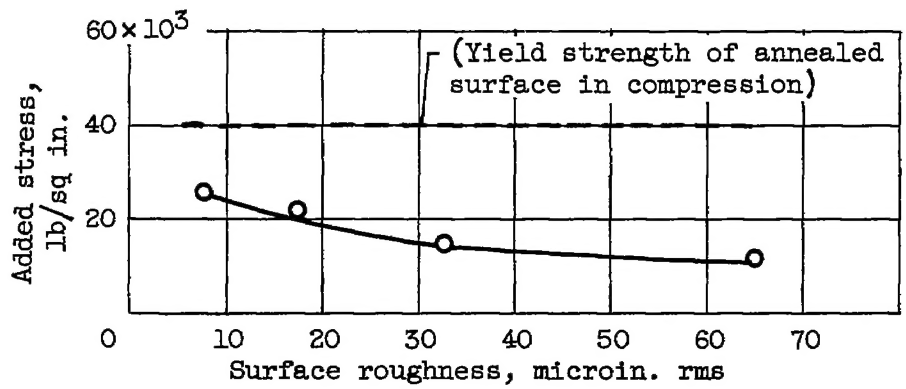

Figure 10. - Additional compressive stress required to cause yielding in abraded surfaces of N-155 strips.

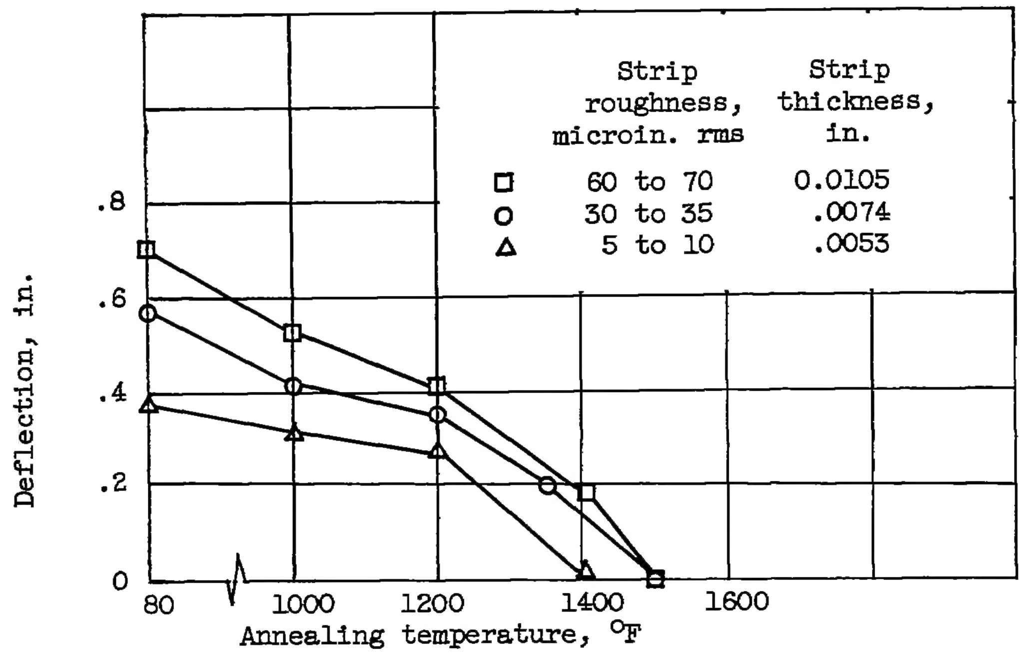

Figure 11. - Effect of temperature on relief of residual stresses placed in surface of strips of N-155 by abrading surface with abrasive papers and cloths. Strips held at each annealing temperature for 4 hours.

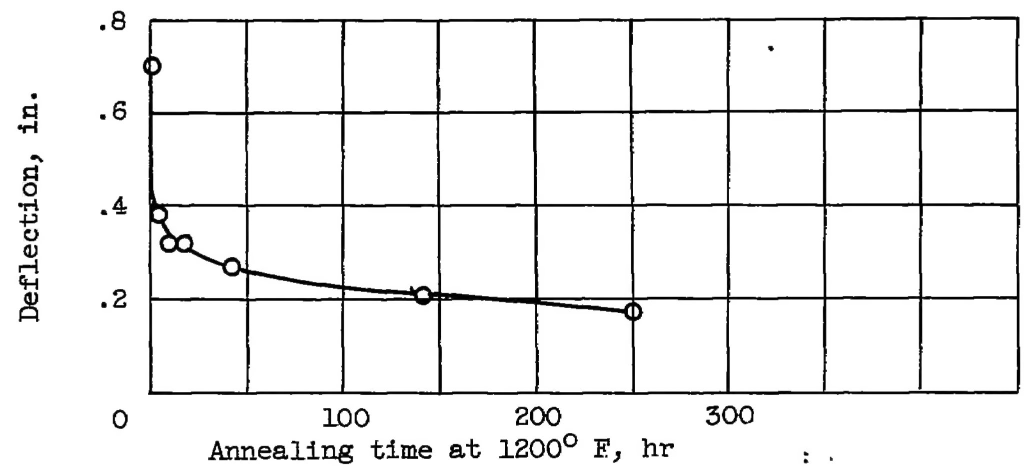

Figure 12. - Effect of time at temperature on relief of residual stresses placed in surface of strips of N-155 by abrading surface with abrasive papers and cloths. Strip with surface roughness of 60 to 70 microin. rms.